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EXAMINING THE DYNAMIC RESPONSE OF MONUMENTAL OBJECTS

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Abstract

The study of the dynamic behavior of ancient artifacts can provide valuable insights on their vulnerability to earthquake activity. This paper investigates experimentally the influence of the level and frequency of excitation on the dynamic response of replicas of ancient vessels. Two lekythoi of different size were excited by harmonic excitation of increasing amplitude and frequency. It was found that as the frequency of the excitation increased, higher amplitudes of excitation were needed to overturn the objects. In addition, when the friction between the vessel and its support base was small, high frequencies and level of excitation caused intense rocking and large rotation of the vessel around its vertical axis. Furthermore, the frequency content of the response is influenced by the level of excitation since it affects the behavior of the object.

Keywords: *Monument; Artifacts; Lekythoi; Seismic behavior*

Introduction

Monumental objects located in museums are vulnerable to the dynamic vibrations that can be imposed by earthquakes. Several cases of damaged statues and artifacts have been reported after strong earthquakes [1, 2]. Understanding the behavior of these objects under dynamic excitations can lead to finding ways to protect them.

Past research focused mostly on the dynamic behavior of regular parallelepipedal objects [3-8], finding criteria that can give predictions of their dynamic response. There are, though, some studies that examined the seismic behavior of artifacts that have different geometric properties than the rectangular-shaped objects [9-11]. In addition, several studies explored ways to mitigate the dynamic response of monumental objects [12-17]. Most of these studies were analytical or numerical and there is a need for laboratory testing to verify the numerical findings.

Monumental objects of different sizes and geometrical properties exist in the museums. Each object has its own seismic response. There is, though, a common behavior that characterizes most of them when they are subjected to earthquakes and this common behavior is worth exploring. Past research has explored the earthquake response of ancient freestanding vessels under increasing excitation intensity and examined the influence of the friction between the object and its support base on their behavior [18]. This research builds upon the previous work of the author [18], focusing primarily on the effect of the frequency spectrum of the excitation signal on the dynamic behavior of monumental objects, as well as examining the frequency content of the resulting displacement response. Two lekythoi of different sizes were

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selected for the experimental investigation. The dynamic signals used in the experiments included harmonic and earthquake excitations. The effect of the frequency spectrum and amplitude of the excitation signals was investigated by altering the coefficient of friction between the object and its base of support.

Experimental Investigation

The replicas of monumental objects used in this experimental testing included two different sizes of lekythoi (Fig. 1). The first one was of small size with the following characteristics: height 16cm, base diameter 4.5cm and mass 175gr. The larger lekythos had the following characteristics: height 24cm, base diameter 5.6cm and mass 420gr.

Fig. 1. Photograph of the two vessels used for testing

The objects were placed either one at a time or together on a melamine board, which was secured on a shake table with four metal angles. Furthermore, they were connected loosely with strings from a metal frame to avoid damage from falling.

Initially, it was determined the level and frequency of the excitation that would cause overturning. A harmonic excitation signal with increasing amplitude and frequency was used. The excitation of the base of support of the objects was measured with an accelerometer and a wire sensor.

In order to relate the findings under harmonic excitation with field excitations, in the next set of experiments an earthquake signal was used with a well-distributed energy over the frequency band of 0-8Hz. The displacement of the objects was recorded by three laser transducers. Two were measuring the motion of the top and lower parts of the object along the excitation axis and one the top motion of the object perpendicular to the excitation axis. To avoid losing measurements due to sliding and rocking of the object, lightweight cardboards were attached to the vessels at the parts of the objects where measurements would be obtained. The intention of the excitation was to increase gradually till overturning of the object would occur. Two surfaces of contact were used with coefficients of friction of approximately 0.28 and 0.41 for both objects.

Results and Discussion

Harmonic Excitation

Large Lekythos

The influence that the frequency of the excitation has on the dynamic behavior of the artifacts was examined by exciting their support base with a harmonic signal of increasing frequency and intensity level. Figure 2 presents the value of the peak acceleration and peak velocity at each frequency of excitation that caused overturning of the large lekythos. The peak velocity was obtained by integrating the base acceleration signal. Small changes in the peak velocity with respect to the frequency value were observed. However, the increase of the frequency required higher acceleration amplitudes for the object to overturn. In addition, for the low coefficient of friction, rotation about the vertical axis was noticed for frequencies from 3Hz and higher. The increase of the level of excitation produced intense rocking and large rotation of the object.

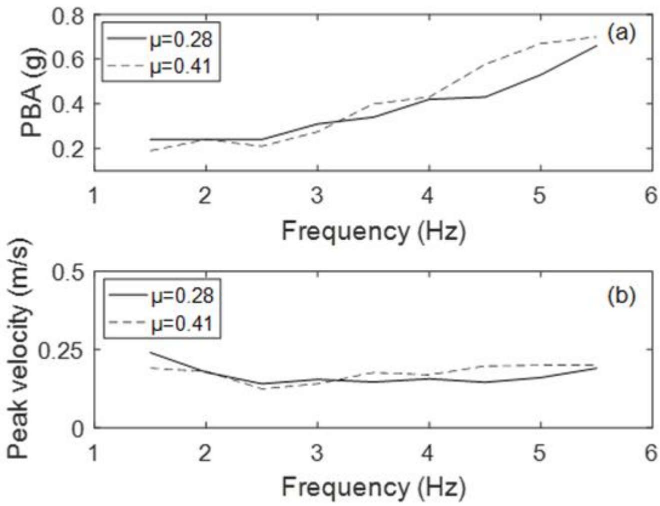

Fig. 2. Response of large lekythos under harmonic excitation: (a) Peak acceleration and (b) peak velocity of the support base causing the vessel to overturn with respect to the excitation frequency

The value of the coefficient of friction affects the behavior of the object. When the coefficient of friction increased, the rotation of the object was reduced and rocking was mostly observed. Also, above 3Hz the level of the base acceleration required for the object to fall increased.

Small Lekythos

The influence of the frequency of the excitation on the dynamic behavior of the small lekythos is presented in figure 3. The peak base acceleration causing the object to fall (Figure 3a) was almost constant up to 3.5Hz. Above 3.5Hz, higher levels of acceleration were required for the object to overturn. The peak base velocity producing overturning of the object was high at low frequencies and decreased till it reached 3.5Hz. For frequencies above 3.5Hz the peak base velocity remained almost constant.

The friction also played a role in the motion of the object. For low friction and for low levels of excitation, mostly sliding along the direction of excitation was observed. At high levels of excitation (0.3g and higher), rocking succeeded sliding, leading to possible overturning. In addition, for frequencies 3Hz and above and for low excitation intensity, the object was sliding with slight rotation about its vertical axis. At this range of frequencies and at high levels of excitation, rocking was observed with increased rotation about its vertical axis and slight translation. Above 5Hz and at high levels of excitation (tested up to 0.7g), the object would slide at the beginning, followed by rocking and rotation (with small translation) without falling.

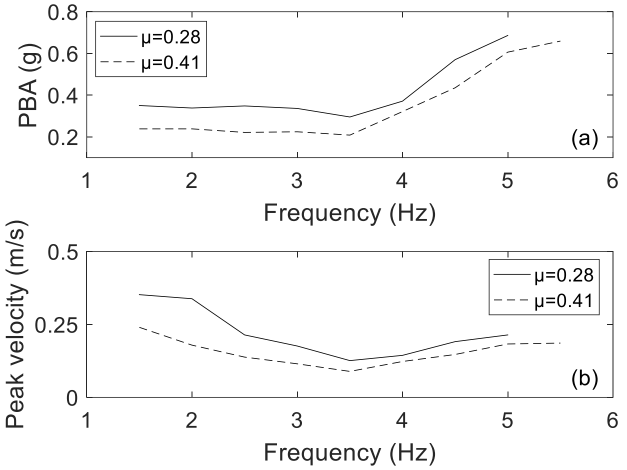

Fig. 3. Response of small lekythos under harmonic excitation: (a) Peak acceleration and (b) Peak velocity of the base of support causing the object to fall with respect to the excitation frequency

Increasing the friction level caused a reduction of the excitation levels necessary for the object to overturn. Rocking in the axis of the excitation was the main motion of the object starting from low levels of excitation. Slight rotation was also observed, but not sliding.

Earthquake Excitation

The two lekythoi were excited by an earthquake signal with a well-distributed energy over the frequency range of 0-8Hz (Fig. 4).

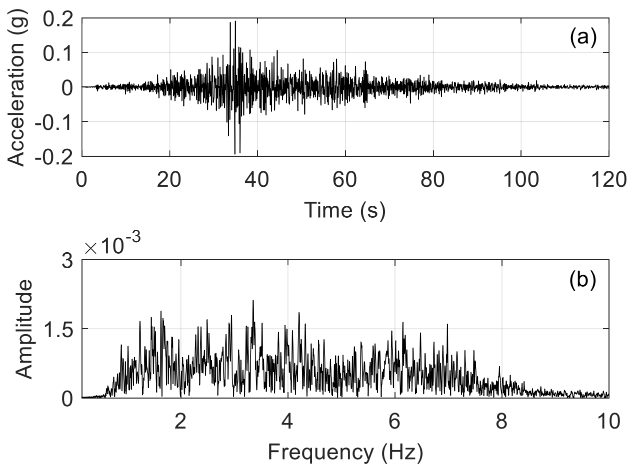

Fig. 4. Base excitation: (a) Acceleration time history; (b) Its frequency spectrum

Large Lekythos

First the large lekythos was set on the melamine board with the low coefficient of friction and it was excited by the earthquake signal. Figure 5 presents the peak displacement of the upper part of the object parallel and perpendicular to the direction of excitation and the peak

displacement of the lower part of the object parallel to the direction of excitation, relative to the peak base acceleration. Rocking started at peak base acceleration close to 0.18g.
The increase of the amplitude of excitation produced intense rocking followed by large rotation of the object around its vertical axis. In addition, at peak base acceleration of 0.2g and higher, the intense rocking could produce falling of the object. Sometimes falling would be avoided with the object finding its balance at the last instance. This behavior is indicated in Figure 5 with the red dot, which corresponds to the lower level of excitation that could produce falling of the object. Figure 6 presents the frequency spectrum of the displacement of the top of the object parallel to the direction of excitation for four different excitation levels. Figures 6a, b, c and d correspond to peak base accelerations of 0.17, 0.21, 0.23 and 0.25g, respectively. The frequency response of the object corresponding to 0.17g was small (solid curve in Fig. 6a); thus, for better comparison with the rest of the plots, its values were multiplied by 10 to make it visible (dashed curve). The energy of vibration of the object shifted to different frequencies with the increase of the level of excitation. The more important change of the frequency spectrum occurred at the highest level of excitation presented in Figure 6d. At that level, the number of peaks of the response increased, including high energy of vibration at frequencies above 3Hz, which explains the observed rotation of the object about its vertical axis (according to the conclusions derived under harmonic excitation).

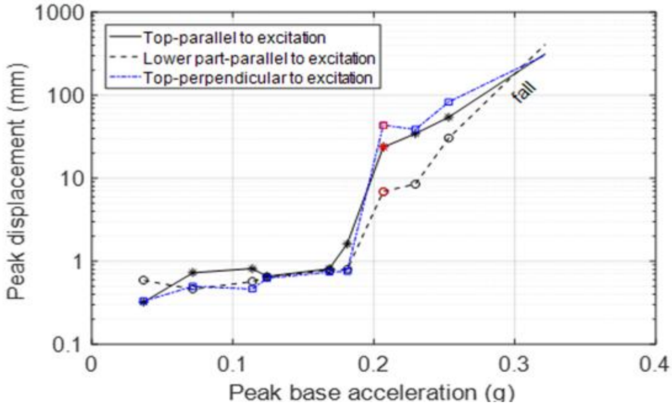

Fig. 5. Peak displacement of the large lekythos under increasing levels of the seismic signal (small coefficient of friction)

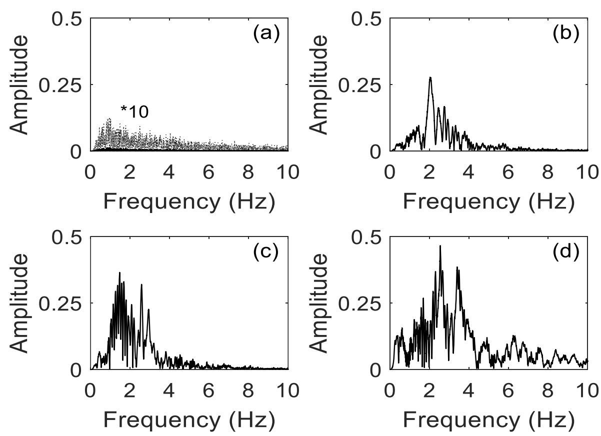

Fig. 6. Frequency spectrum of the response displacement of the top part of the large lekythos along the excitation direction: (a) 0.17g; (b) 0.21g; (c) 0.23g; (d) 0.25g. (Small coefficient of friction)

As the coefficient of friction increased, the predictability of the large lekythos response increased as well. Only rocking in the direction of excitation was observed, which was intensified at higher levels of excitation, leading at the end to overturning of the object. The rocking motion can be observed from the distance that separates the curves that correspond to the displacement of the top and lower parts of the object aligned with the direction of the excitation (Fig. 7).

Figure 8 presents the frequency spectrum of the displacement of the upper part of the object parallel to the direction of excitation for four different excitation levels. Figures 8a, b, c and d correspond to peak base accelerations of 0.14, 0.18, 0.22 and 0.24 g, respectively. There is a small shift of the spectrum to lower frequencies at the higher levels of excitation with an increase in amplitude. There is no energy at high frequencies that would indicate rotation of the object.

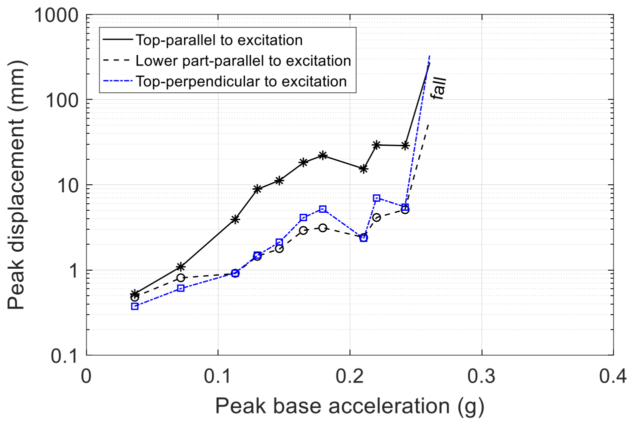

Fig. 7. Peak displacement of the large lekythos under increasing levels of the seismic excitation (large coefficient of friction)

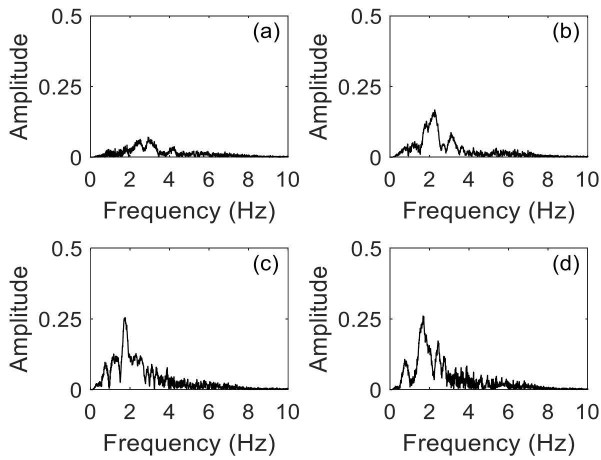

Fig. 8. Frequency spectrum of the response displacement of the upper part of the large lekythos along the excitation direction: (a) 0.14g; (b) 0.18g; (c) 0.22g; (d) 0.24g. (Large coefficient of friction)

Small Lekythos

The seismic response of the small lekythos, for low friction levels, was sliding parallel to the direction of the excitation. This can be observed in Figure 9 with the two curves corresponding to the peak displacement of the top and bottom part of the vessel parallel to the direction of excitation almost coinciding. The increase of the level of excitation invoked not only sliding but rocking and rotation around its vertical axis which at high levels of excitation caused overturning of the object (Fig. 9).

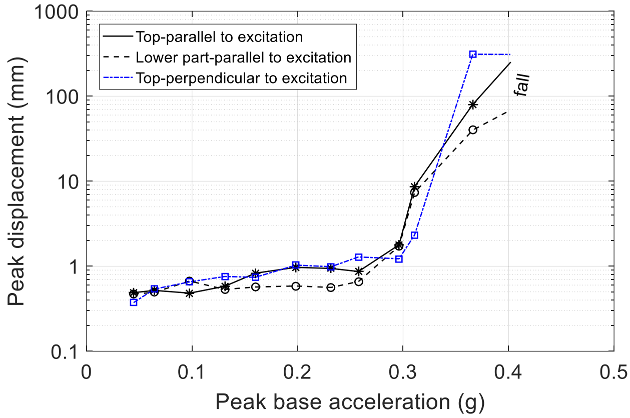

Fig. 9. Peak displacement of the small lekythos under increasing levels of the seismic excitation (small coefficient of friction)

Figure 10 presents the frequency spectrum of the displacement of the top of the object parallel to the direction of excitation for four excitation levels of increasing amplitude. For better visualization of the response, Figure 10d was selected to have different y-axis limits than the rest of the subplots (indicated by the blue color). The frequency spectrum changes considerably with the increase of the amplitude of the excitation. At low levels of excitation (Fig. 10a and b) only small sliding was observed with the energy of the response concentrated at lower frequencies. The increase of sliding of the object and rocking and rotation around its vertical axis (Fig. 10c and d) changed the response involving higher frequencies.

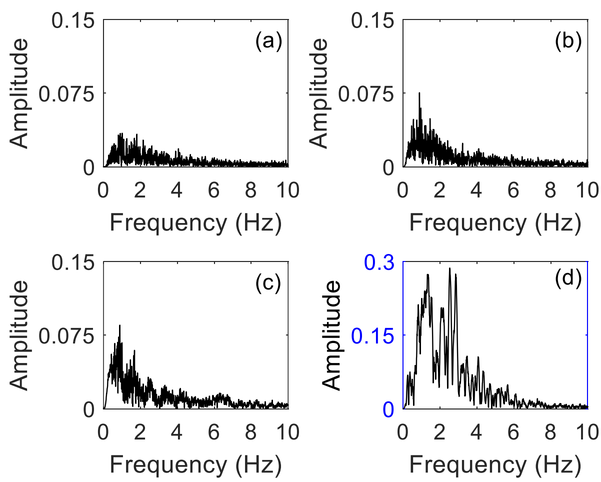

Fig. 10 Frequency spectrum of the response displacement of the top part of the small lekythos along the excitation direction: (a) 0.2g; (b) 0.26g; (c) 0.31g; (d) 0.36g. (Small coefficient of friction)

The increase of the coefficient of friction changed the behavior of the small lekythos. The only motion observed was rocking parallel to the direction of excitation (Fig. 11). The influence of the friction level was significant, producing falling of the object at peak base acceleration close to 0.2g.

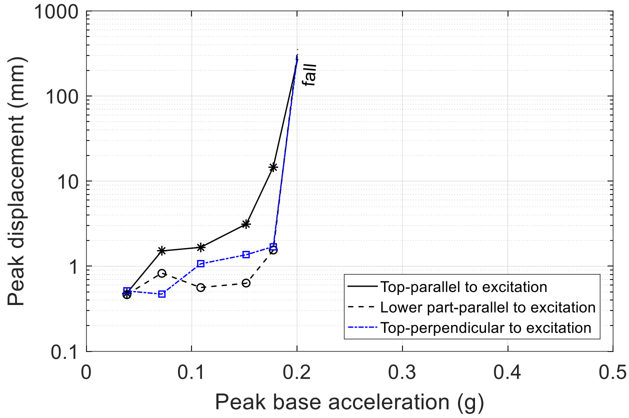

Fig. 11. Peak displacement of the small lekythos under increasing levels of the seismic excitation (large coefficient of friction)

Figure 12 presents the frequency spectrum of the displacement of the top of the object parallel to the direction of excitation for four different excitation levels of increasing amplitude. Only rocking was observed parallel to the direction of excitation. The shape of the spectrum is similar for all excitation levels, with increasing amplitude as the level of excitation increased.

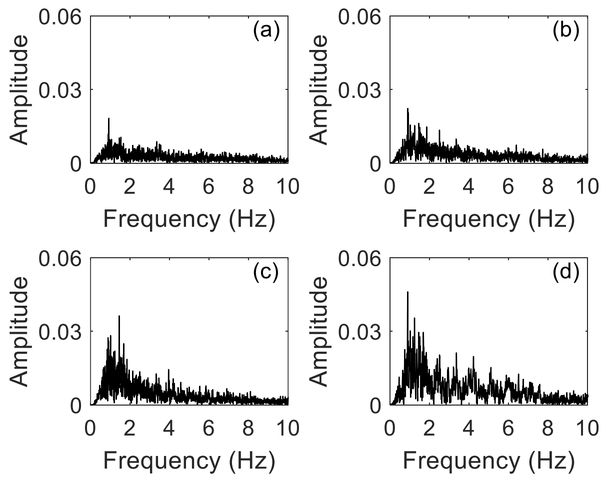

Fig. 12. Frequency spectrum of the response displacement of the top part of the small lekythos along the excitation direction: (a) 0.06g; (b) 0.08g; (c) 0.11g; (d) 0.16g (Large coefficient of friction)

Discussion

The geometric properties of the two lekythoi have a significant impact on their dynamic behavior. According to theory, the most important geometric parameter that affects their dynamic response is the ratio of half of the base diameter of the object (b) with respect to the distance of the object's center of gravity from its support base (h). For sliding to occur [8] the peak base acceleration with respect to the acceleration of gravity (a_g/g) has to be smaller than b/h and greater than the coefficient of friction. Sliding was observed only for the small lekythos and for the small coefficient of friction satisfying the aforementioned conditions. *A. Papalou* [18] though observed that for other excitation signals and other vessel's geometry the first of these conditions may be exceeded.

It is notable the change of the frequency spectrum of the response with the increase of the seismic excitation level for the small coefficient of friction. The peaks of the frequency spectrum shift, depending on the behavior of the vessel. The rotation of the objects adds energy in frequencies higher than 2Hz which is consistent with the findings corresponding to the harmonic excitation. The coefficient of friction plays a significant role since it reduces the rotation of the object reducing the energy in the high frequencies. Large sliding of the object gives peaks at several frequencies with most of the energy concentrated at the lowest one.

Conclusions

The dynamic response of replicas of ancient objects with different geometrical properties was studied experimentally under harmonic and earthquake excitations. It was found that increasing the frequency of excitation requires intense excitation levels for the object to fall. In addition, high frequencies and levels of excitation produce intense rocking which, when the coefficient of friction is small, leads to large rotation of the object. The frequency spectrum of the seismic response displacement of the objects changes as the level of excitation increases. Not only the amplitude of the response increases with the increase of the level of excitation but also the frequencies of vibration do not remain constant. In addition, the rotation of the object about its vertical axis increases the response amplitude at higher frequencies.

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